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Dynamic Verification of a Grid Structure Numerical Model Consisting of Different Stiffness Parts

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Abstract

The work presents the results of experimental and numerical investigations into the natural frequencies of grid structure containing parts made of materials with significantly different elastic modulus. A good example of such structure is human thorax. Firstly, the elastic properties of bone and cartilage materials were obtained by using bending and compression tests. The elastic modulus of the compact substance of the bone is 8…12 GPa, coastal cartilage – 70…90 MPa. The maximum failure force and bending strength were defined under the bending impact test (using a drop tower impact system). This bone strength is ~175 MPa (1.5...2 times more of the values obtained in static bending). Then, a three-dimensional model of a human thorax was developed allowing one to predict their mode shapes and the natural frequencies using the finite element method (ANSYS software). The verification of the model was carried out by comparing the experimental (in vivo) and numerical natural frequencies of a human thorax.

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Keywords: mechanical properties; natural frequency; numerical modeling; finite element method; human thorax.

1. Introduction

Grid structures constitute a significant class of modern technology constructions (frames of a vehicle such as trams, buses, trains), which are generally used, metallic materials with similar values of the elastic moduli [1-3]. Research methods of its dynamic characteristics (mode shapes and natural frequencies) have been well studied [1, 3-6]. The living objects have large difference of mechanical properties of the materials as opposed to technical objects.

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A good example of a responsible grid construction may be human rib cage, which consists of the bone and cartilages [7, 8]. Local impact to the human thorax can lead to a bone fracture and internal injuries. Body armors are used preventing this type of injury [9-13]. There are a small number of papers where authors study the mechanical properties of biological tissues and create different level models (analytical and numerical ones) [8, 10, 14-16].

It is well known that biological tissues have a wide spread of the mechanical properties, which are also dependent on the strain rate [8, 17- 21]. The CPU time depends on the detalization level of the task. Model can give answers to a few specific questions (low-parametric model) or indefinitely large number of questions (e.g., cases of loading) – three-dimensional detailed model with parts having very different elastic and strength properties. Two big problems are in this routine: proper mechanical properties of tissues and appropriate verification procedure of models.

In this work, mechanical properties of swine bone and cartilage were defined by tests. The swine materials were investigated as a model materials because properties are analogous to the characteristics of a human tissues. The obtained experimental data were used in the three-dimensional numerical model of human thorax to determite natural frequencies (two model: without and with soft tissues). Verification procedure on real humans has the definite pain limitation. The models were verified by a comparison of the natural frequencies of human thorax with the experimental data (obtained in vivo by slight impact in sternum bone).

2. Experimental and computational parts

Experimental data of mechanical properties were used by quasi-static and dynamic tests and investigation of natural frequencies of human thorax under impact. All experiments were carried out on the equipment of research and education center “Experimental Mechanics” of South Ural State University. The data obtained were used below in the numerical three-dimensional model of the human thorax.

2.1. Experimental determination of mechanical properties of the bone

Experimental investigation of mechanical properties of bone was performed under static and dynamic bending tests (universal test machine Instron 5882 with loading rate 40 mm/min and drop tower impact system Instron CEAST 9350 – impact speed 2 m/s). Sample tested in three-point bending scheme, the distance between the hinge supports is 90 mm. Curves “force – displacement” were obtained (fig. 1). Ribs cross-section has a tear-drop shape, which replaced solid ellipse or thin-walled elliptic shapes. Table 1 shows the values of the elastic modulus, ultimate strength of the bone.

Table 1. Characteristics cross-section of rib in influence area.

Specimen	Test	Length of sample (*mm*)	Elastic modulus (*GPa*)		Ultimate strength (*MPa*)	
			Elliptic cross-section	Thin-walled elliptic cross-section	Elliptic cross-section	Thin-walled elliptic cross-section
1	Static	160	5.3	10.2	71	127
2		140	4.3	8.8	59	85
3		130	5.8	6.3	73	80
4	Dynamic	170	11.3	18.3	115	177
5		190	7.6	12.5	114	175

Mean elastic modulus of the bone is 5.1 GPa for solid elliptic cross-section, and 8.4 GPa for thin-walled elliptic cross-section by reducing bending static diagrams. Mean bending strength are 68 MPa for solid elliptic cross-section, and 97 MPa for thin-walled elliptic cross-section. Value of ultimate strength of material at dynamic test was substantially larger than quasi-static one. Mean elastic modulus of bone is ~8.0 GPa, bending strength is ~120 MPa for solid elliptic cross-section. Data of flexural modulus of the compact bone substance are lying from 3 to 20 GPa (ref. [17, 22]). It is worth noting that bone is inelastic behavior.

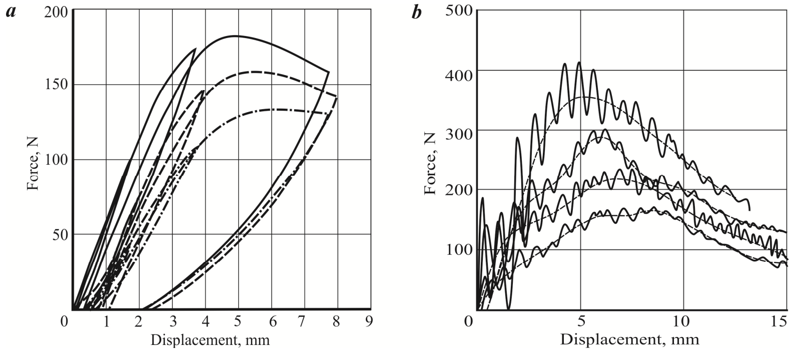

Fig. 1. Diagrams "force – displacement" under (a) static and (b) dynamic tests.

2.2. Experimental determination of mechanical properties of the costal cartilage

Mechanical properties of cartilage were determined under cyclic compression with universal testing machine Instron (model 5882). Specimens were compressed using flat plates with loading rate of 1 mm/min at room temperature. Stress – strain diagram is shown in fig. 2. Cross-section of specimen is a solid ellipse.

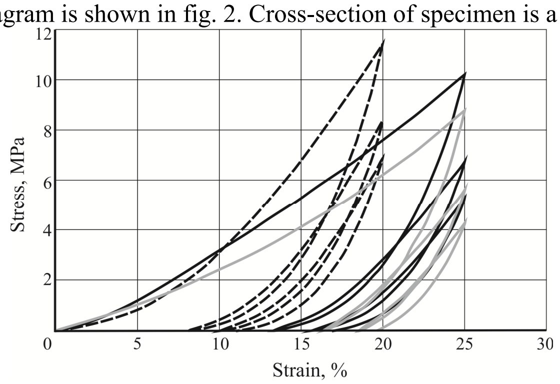

Fig. 2. Engineering compressive stress – strain diagrams of the costal cartilage.

Specimens were cyclic compressed to strain 20 and 25% with next unloading. Mean elastic modulus of cartilage is defined with the initial part of the unloading curve, because cartilage is viscoelastic material. Mean elastic modulus of cartilage is 90 MPa, which is in a good agreement with published data [23].

2.3. Investigation of natural frequencies of the human thorax

Experimental investigation of natural frequencies of the human thorax

Local impact and measured damped oscillations were carried out in the center of the sternum, which have minimum thickness of the soft tissues. The tests were conducted as follows: a person sitting right leaning back in his chair; piezoelectric accelerometer (PCB Piezotronics T356A32, 100 mV/g) was fixed about 100 mm from the upper point of sternum (incisura jugularis) by using double-sided scotch tape. Local impact (Impact Hammer PCB 086C03, 2.25 mV/N) made in the region (above the sternum to the accelerometer 50 mm) at inhalation, exhalation and middle position. Fig. 3 shows the corresponding curves “acceleration – time”.

Experimental diagram “acceleration – time” were reduced by MathCad and PowerGraph software to obtain frequency spectrum of response, that shown in table 2. It should be noted, that all natural frequencies of human thorax are not excited and registered under impact. For example, this is typical of symmetrical shapes of bodies.

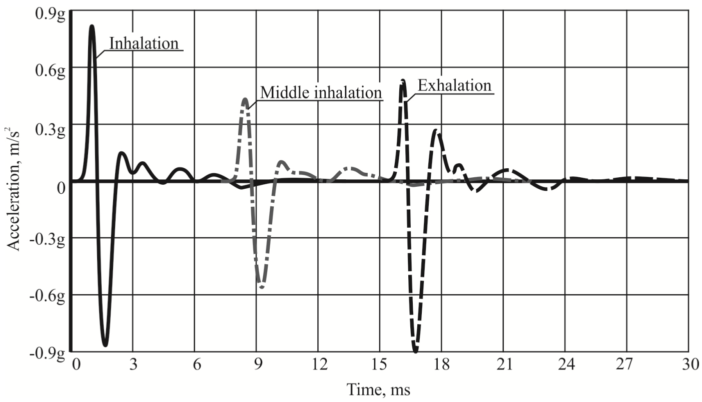

Fig. 3. Diagrams "acceleration – time" at the center of the sternum (in the direction normal).

Mean value (three experiments) natural frequencies are not very different for different breath positions, which is not exceeded in the range of engineering errors.

Table 2. Mean values of three natural frequencies of human thorax under impact in the sternum.

Number of frequency in the spectrum	Experimental natural frequencies (*Hz*)			Calculated natural frequencies* (*Hz*)	
	Inhalation	Middle inhalation	Exhalation	Model 1 (without soft tissue)	Model 2 (with soft tissue)
1	3.17	2.63	3.22	20.62	6.09
2	14.34	-	16.12	37.45	14.91
3	15.99	15.63	19.20	59.24	16.50

* see below

Numerical modelling of human thorax

Three-dimensional model of the human thorax (height 165 cm, weight 50 kg, chest girth 64 cm, mesomorphic/somatotonic) was created with SolidWorks software. Model of human thorax is consisted by sternum, 12 thoracic vertebrae and intervertebral discs, 24 ribs and costal cartilages. The assumption of this model – ribs and sternum presented in the form extended solid elliptical cross-sections along the contour, all processes of vertebra, scapula, clavicle, the internal organs are excluded (fig. 4). All elements of model (ribs, cartilage, vertebrae, intervertebral discs and sternum) were bonded. Displacement and rotate of surface of 12th thoracic vertebra were fixed.

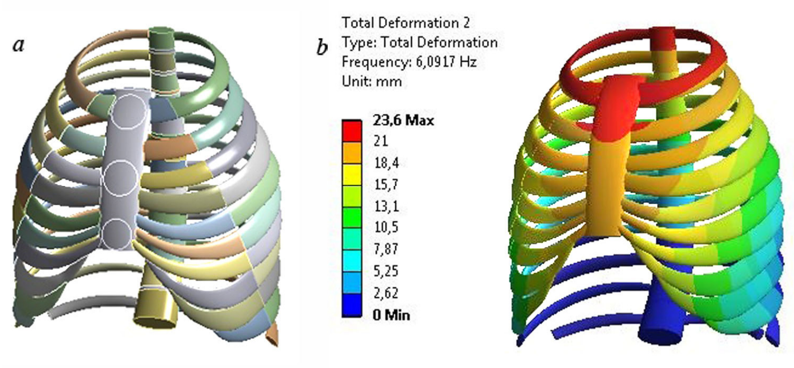

Fig. 4. Model of human thorax (a) and first mode shape (b).

The natural frequencies are determined to considering two models (with and without superficial soft tissues, which included in the scheme of model in the form of increased density of the material). Mechanical properties of bone and costal cartilage are presented in table 3.

Table 3. Mechanical properties of the human thorax material.

Material	Density (*kg/m*^{3})	Elastic modulus (*MPa*)	Ultimate strength (*MPa*)	Poisson's ratio
Bone	1 200 / 24 000*	$8\cdot10^3$	120	0.30
Cartilage	1 100 / 22 000*	90	50	0.42

* Density with involving of soft tissues. Increased density of cartilage for only intervertebral discs.

In table 2 shown numerical results of three natural frequencies of human thorax. The first model (without soft tissue) had higher values of frequencies, while the second (with soft tissue) shown quite satisfactory result. Thus, second model was verified.

2.4. Intensive impact in the sternum through a body armor

Using verified three-dimensional model of the thorax performed to estimate the displacement under impact by bullet of TT pistol (weight 5.49 g, speed of 440 m/s) in the sternum through a body armor for protection class 2 in accordance with GOST R 50744-95 (areal density of 10 kg/m²). In this case, cylindrical disk (mass 32 gm and diameter ~50 mm) contacts human thorax at a velocity of 57 m/s. Cartilage was assumed an elastic material but bone behaviors were an elastoplastic with a yield stress of 120 MPa. The strain distribution of the thorax (sternum and cartilage) at a time of 0.25 ms was estimated using numerical method – FEA (ANSYS Workbench, Transient mechanical), Fig. 5. Maximum of the first principal stress in the sternum is more than yield limit of material (bone), which indicates the possibility of serious injury and the need for care. However, this strain is not caused large displacement of sternum in the heart region and it is around 10 mm. This displacement should be less than 44 mm in accordance to standard NIJ 0101-06.

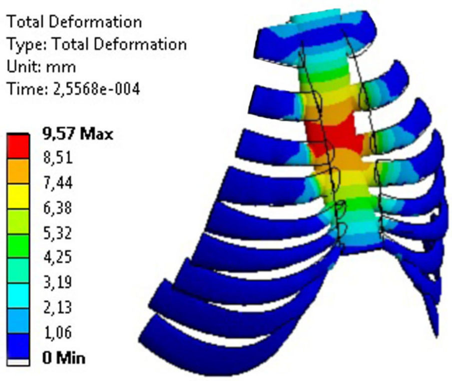

Fig. 5. Strain distribution of the human thorax center part under impact through the body armor.

3. Conclusions

In this work, the three-dimensional numerical model of grid structure (human thorax) was designed. This model allows defining natural frequencies and mode shapes (under low velocity impact) and injury (under intensive local impact). Mechanical properties of the materials were investigated under static and dynamic tests, because they are sensitive to strain rate.

It was shown that the sternum is experiencing inelastic strain under impact of pistol TT bullet in soft body armor class 2. But the dynamic displacement is not sufficient for injury of internal organs.

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